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Tiber River-Driven Chlorophyll-a and Total Suspended Matter Dynamics and Their Impacts along the Central Tyrrhenian Sea Coast: A Sentinel-2 Approach

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ABSTRACT

Chlorophyll-a (Chl-a) and Total Suspended Matter (TSM) are key health indicators of the coastal ocean and seas. The former is linked to primary productivity, while the latter is associated with water quality; both are influenced by change in climate. Recent studies have highlighted a declining trend in Chl-a levels along the Mediterranean coastal region. River discharge plays an important role in regulating the coastal Chl-a concentration levels. The present research primarily focuses on understanding the significance of Tiber River −driven spatial dynamics of Chl-a and TSM along the central Tyrrhenian Sea coasts. The research also focuses on evaluating the applicability of Sentinel-2 and identifying a suitable method for estimating Chl-a and TSM from Sentinel-2. Neural networks and dark spectrum fitting techniques were applied using multiple algorithms to estimate the dynamic distribution of Chl-a and TSM driven by the Tiber River in the study area. Multiple statistical analyses were performed, and statistically significant relationships were observed. The Case-2 Regional Coast Colour Neural Network (C2RCC-Net) outperformed all other algorithms, with an R^2 value of 0.903 for Chl-a and an R^2 value of 0.966 for TSM. Furthermore, the present research also identified a positive pixel to pixel spatial correlation between Chl-a and TSM in all four seasons, highlighting the positive impact of Tiber River on maintaining Chl-a levels along the coasts of Tyrrhenian Sea. This stands in contrast with the negative trend seen in the Mediterranean scale.

1. Introduction

Chlorophyll-a (Chl-a) and Total Suspended Matter (TSM) are the primary health indicators of the coastal ocean and seas. The former is linked to primary productivity, while the latter relates to water quality, and both are influenced by climate change. Chl-a serves as a critical indicator of marine ecosystem health, directly associated with phytoplankton abundance and primary productivity (Colella et al., 2016). Likewise, TSM play a vital role as a water quality indicator, reflecting the concentration of suspended particles, and organic matter (Cummings et al., 2020). Phytoplankton: foundation of marine food web and are directly connected with the fishery yield, any disturbance could have a substantial impact on the marine ecosystem (Cheung et al., 2010). Factors affecting phytoplankton biomass includes climate change, anthropogenic activities (Marrari et al., 2017), sea surface temperature (Zhang et al., 2023), marine heat waves (Noh et al., 2022). Marine Chl-a concentrations are primarily dependent on the nutrient availability and the Mediterranean marine ecosystem is not highly nutrient-enriched (Kotta and Kitsiou, 2019). As the prime component of the marine food web the Chl-a level is directly proportional to the overall marine health and productivity (Bot and Colijn, 1996; Gilbert et al., 2000). Efficient monitoring of Chl-a provides a comprehensive understating of nutrient cycle (Lundsør et al., 2020).

The Tiber River, Italy's second largest river in in terms of volume of transport, is a significant contributor to the Tyrrhenian Sea. To a certain extent, sediment loads from the river have a significant influence on the regional marine ecosystems (Baird et al., 2021; Ge et al., 2020; Xu et al., 2020). Excessive TSM has profound impacts on light penetration, nutrient availability (Caballero et al., 2019) incidence of harmful algal blooms (Legleiter et al., 2022), and the overall health of the marine ecosystem (Bannister et al., 2012). In general, TSM constitutes nearly eighty percentage of the total river discharge, with a size range of 0.45

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μm and 2000 μm (Mohsen et al., 2022). Human induced River sediments load has a profound negative effect on the marine ecosystem (Álvarez-Romero et al., 2014; Rangel-Buitrago et al., 2023). The excessive amount of nutrients and turbidity and minimize the light availability (Fredston-Hermann et al., 2016) and high concentration of TSM leads to the light attenuation and adversely affects the marine habitats and primary productivity (Díez-Minguito and de Swart 2020; Wang et al., 2019).

The Tyrrhenian coast possesses a dynamic marine ecosystem where bio-chemical and physical processes evolve over short temporal scales (Lapucci et al., 2012). Recent studies have shown that substantial increases in extreme coastal events, including heavy rainfall, river floods and storm surges (Song et al., 2023). The freshwater flow develops a characteristic circulation pattern driven by the horizontal pressure gradient created by the difference in sea water and freshwater densities (Mann and Lazier 2005). The less dense fresh river water enters the sea surface layer, inducing a bottom flow that carries a dense seawater mass from the open sea into the estuary's interior. This process leads to resuspension of the nutrients from the seabed (Nunes Vaz and Simpson 1994). The behaviour of fluvial inputs is regulated by dynamic processes (wave currents, general circulation, tidal currents) with compounding effects arising from multiple factors. These include geomorphological factors like prevailing wind, bathymetry and shoreline (Bonamano et al., 2024). Tiber river plume's dynamic scale span a range, from meters to more than 100 km depends on the prevailing weather and oceanographic conditions (Inghilesi et al., 2012).

Marine remote sensing of Chl-a face challenges due to several factors, which includes cloud cover conditions (Zheng and DiGiacomo, 2017), wave conditions and high turbidity (Cui et al., 2020). Recent advancement in remote sensing technologies holds the potential to estimate the Chl-a concentration globally at various scales; hence, it is recognized as an important factor in the climate studies (Hammond et al., 2020). Satellite information with superior capabilities is a prerequisite for gaining a deeper understanding of Chl-a and TSM dynamics and its impacts on the study area. Compared to existing freely available satellite information, Sentinel-2 possesses superior spatial, spectral, and temporal characteristics, making it highly suitable for frequent monitoring and comprehensive assessment of Chl-a (Clevers and Gitelson, 2013; Nababan' n.d.) and TSM (Niroumand-Jadidi et al., 2022).

Over the last decade, there has been a significant increase in the use of remote sensing technologies in water quality and related studies (Yu et al., 2022). Advance in spatial, temporal resolutions with freely accessible satellite information plays majorrole in water quality studies particularly in Chl-a and TSM (Aranha et al., 2022). Considering the time and space limitations of conventional in-situ methods (Saberioon et al., 2020), freely available high-resolution Sentinel-2 provides continuous monitoring of Chl-a and TSM which is paramount in the field (Jiang et al., 2023; Saberioon et al., 2020). Severalare methods available for retrieving Chl-a and TSM from Sentinel-2, (Bramich et al., 2021) observed that enhanced Sentinel-2 red edge band-based algorithms are more effective in compared to existing band ratio algorithms. The C2RCC is another proven atmospheric correction method and applied for estimating Chl-a and TSM (Ogashawara et al., 2021), however its highly sensitive to land and water interface particularly over narrow and small water bodies (Ansper and Alikas, 2019). (Shaik et al., 2021) Compared sentintil-2 and sentinel-3 informations for estimating the Chl-a in the turbid marine water, the results show that's the Sentinel-2 based MCI (Maximum Chlorophyll Index) outperformed Sentinel-3 based MCI and registered a higher correlation with the in-situ data. However, in another research over the Baltic Sea, the sentinel-3 outperformed Sentinel-2 in correlating with the in-situ data (Soomets et al., 2022). Currently, there are no widely accepted algorithms for retrieving Chl-a and TSM in coastal waters from remote-sensing reflectance (Zheng and DiGiacomo, 2017). Unlike open oceans, where phytoplankton influence the optical properties of water, in Case II waters, the absorption of light by photosynthetic pigments is less significant compared to optical components originating from the land, such as dissolved and particulate organic and inorganic matter. These components have a significant impact on light absorption and scattering in water but do not mostly correlate with phytoplankton levels.

Consequently, it is necessary to regionally validate the performance of algorithms using in situ data to ensure accurate retrieval of Chl-a and TSM in case II waters. Advancements in remote sensing technology coupled with machine learning techniques offer promising solutions for efficient and accurate Chl-a and TSM estimation in coastal waters. Advanced machine learning algorithms, includes Random Forest, Artificial Neural Networks and Support Vector Machine, can efficiently generate Chl-a and TSM from remotely sensed information. One of the key advantages of machine learning based Chl-a retrieval is its ability to capture spatial and temporal variability in coastal waters. By analyzing large datasets of satellite observations and corresponding Chl-a and TSM in-situ measurements, machine learning models can discern patterns and trends, improving the accuracy of the estimates across diverse coastal environments. A holistic approach is necessary to fully understand its dynamic nature and distribution of Chl-a and TSM, particularly concerning the influence of the Tiber River. The change in climate and ever-increasing human activities altered the bio-chemical characteristics of the marine environment, which has a profound impact on the marine Chl-a and the TSM. This research focused on assessing the role of the Tiber River, analysing the spatio-temporal distribution od Chl-a and TSM and assessing their influence on the central Tyrrhenian marine ecosystems.

2. Study area

The area of interest for this research lies between Capo Linaro to the north and Capo d'Anzio to the south (central Latium, Italy), extending over a stretch of coast of approximately 100 km and up to the limit of the continental shelf towards the open sea. The Tiber River, with its strong influence, is the primary river in central Italy and the second largest in the country. It has a hydrographic basin covering 17,156 km^2 and spans a length of 409 km (Pitarch et al., 2019). It rises into the Tuscan-Emilian Apennines Mountains, and it is limited to the east by the carbonate ridge of the Umbria-Marche Apennines, while the western sector is mainly occupied by the Tuscan-Marchean volcanic reliefs. Near the mouth, the course of the river is abruptly diverted towards the west by the volcanic apparatus of the Alban Hills (Chiocci and La Monica, 1996). Tiber River flows through six Italian regions namely, Emilia Romagna, Tuscany, Latium, Umbria, Marche, and Abruzzo and, after crossing the city of Rome, characterized by a strong anthropization, it reaches the Tyrrhenian Sea with a delta cusp located in the centre of the physiographic unit. The main branch, called Fiumara Grande, is the natural mouth of the river; the smaller one, called Fiumara Piccola, is an artificial channel which ends in the town of Fiumicino (Rome), approximately 3700 m north of Fiumara Grande (Fig. 1). The Tiber River hydrologic regime has a key role in sediment transport (Pitarch et al., 2019) with an average flow of 230 m^3/s (Montuori et al., 2016), the maximum annual discharge exceeding 1500 m^3/s and minimum annual discharge reaching 60 m^3/s. High discharges recorded during the winter and low flow rates in the summer season (Iadanza and Napolitano 2006).

Similarly, during the summer season, the solid flow rate is at its minimum, while it reaches its maximum in the autumn and winter seasons. Approximately 90 % of the total sediment load is composed of suspended sediments, with only a minor portion consisting of bed load (Pitarch et al., 2019). The Tiber River delta has a strong influence on the morphology and sedimentology of the coast, consisting mainly of sandy deposits except for the northern and southern portions near the two capes, where rocky coasts can be found. In addition to the Tiber River, there are 13 minor hydrographic basins along the study area characterized by torrential regimes. The submerged delta structure of the Tiber was described by (Bellotti and Tortora, 1985) as a front extending from the coast to a depth of 50 m, with slopes that range between 0.4 and 2 %,

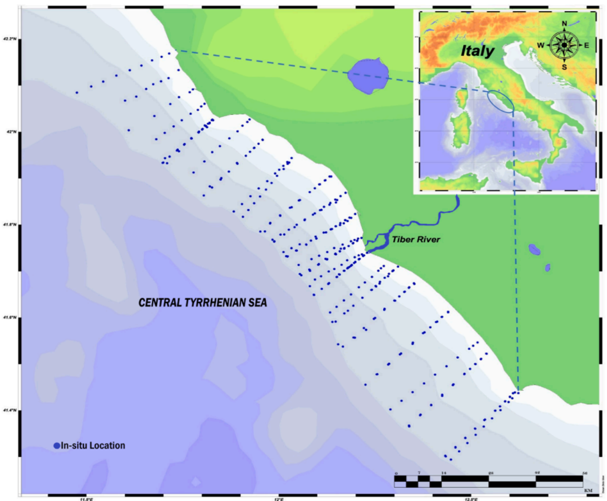

Fig. 1. Study area with In-situ data location.

and a morphology that reflects the coastline pattern, except for the northern sector, where rocky outcrops of important ecological value are reported. Moving southwards the shoals of Macchia Tonda (inside the Macchia Tonda Regional Natural Reserve). Secche di Tor Paterno is a marine protected area of ecological importance located south of the Tiber River mouth, 4–7 miles from the coast, with depths ranging from 18 to 60 m.

3. Methods and materials

3.1. Sentinel-2 properties and processing

The Sentinel-2 satellites emerged as a key player in the field of marine remote sensing. Compared to existing freely available satellite products, Sentinel-2 with its high spatio-temporal resolution, has accelerated unprecedented research possibilities in Chl-a and suspended matter related studies. The Sentinel-2 constellation includes two satellites, Sentinel-2A and Sentinel-2B, launched in June 2015 and March 2017, respectively. The Sentinel-2 spatial resolution of ranges from 10 m to 60 m, and the 12 bits radiometric resolution significantly increases the applicability of monitoring and quantifying the Chl-a-and TSM concentration level. The five days of revisiting capabilities of Sentinel-2 will be an added advantage of capturing the dynamic changes in the coastal ocean and seas. Detailed information regarding the Sentinel-2 properties and capabilities shown in Table1.

Superior spatial, spectral, and temporal characteristics of sentinel 2, are highly suitable for continuous monitoring and comprehensive impact assessment of Chl-a and TSM in the Tyrrhenian region. The present research makes use of both Sentinel-2 A&B, level 1c information, acquired from Copernicus. Sentinel-2 L1C data collected for the period of December 2015 to September 2023, under 30 % cloud condition, a total of 281 satellite data were processed to estimate the Chl-a and TSM. For the better understanding of the spatio-temporal changes, data were categorized into Spring, Summer, Autumn, and Winter. Spatial resolution of Sentinel-2 bands ranges from 10 m to 60 m, to maintain the data consistency, accuracy and considering the research area extent, Sentinel-2 data is upscaled to 60 m for the present research using nearest neighbourhood interpolation method. For precise extraction of valuable information in interest, the land area is masked out to exclude the inland water information. Sentinel-2 Level 1c products were used for the estimation of Chl-a and TSM. More details about the Sentinel-2 characteristics are provided in Table 1.

3.2. In-Situ data

A series of surveys were conducted in the central Tyrrhenian Sea to investigate the influence of the Tiber River. The surveys were carried out between 2020 and 2022, covering different seasons and marine climatic conditions to study the varied behaviour of the river plume. Altogether, 185 stations were sampled across the study area (Fig. 1), with matching satellite data. The in-situ data were collected on the same day as the Sentinel-2 overpass, with the satellite passing over the study area at 10:00:29 and the in-situ data collected between 09:30:00 to 10:30:00. In the central part of the study region, the Tiber River along with its branch converge with the sea in adjacent areas. At each station, vertical profiles were obtained using multi-parametric probes (CTD), for estimating temperature, salinity, pressure, Chl-a and TSM. The present research makes use of Whatman GF/F glass microfibre filters with a 0.7 µm pore size for the analysis of Chl-a and Whatman GF/C glass microfibre filters with a 1.2 µm pore size for the analysis of TSM. To analyse the concentrations level of Chl-a and TSM, water samples were taken from each station using 10*L* Niskin bottles. These samples were used for the calibration of the data derived from the fluorometer integrated into the CTD, following the standard procedures (ISO 1992) (Lazzara et al., 2010). Pre-filtration procedures were carried out to remove mesozooplankton and larger particles using a 250 µm pore size mesh, with the filtered samples stored in 5L PTFE containers at 4 °C. Subsequently, 2-3L pre-filtered samples were further filtered onboard using Whatman GF/F filters. These filters were stored at −20 °C in 100 % acetone and analyzed in the laboratory using a UV-mini-Shimadzu spectrophotometer according to (Jeffrey and Humphrey 1975; Lazzara et al., 2010). Finally, samples for the analysis of TSM were collected in 2L plastic containers. Sub-samples of 1-2L were filtered using pre-dried and pre-weighed glass fibre filters and analyzed according to (Strickland and Parsons 1968) in the laboratory.

Table1
Sentinel-2 characteristics.

Band No.	Spatial resolution(m)	Sentinel-2 A		Sentinel-2B		SNR @ Lref
		Central wavelength(nm)	Band Width (nm)	Central wavelength (nm	Band Width (nm)	
B1	60	442.7	20	442.3	20	129
B2	10	492.7	65	492.3	65	154
B3	10	559.8	35	558.9	35	168
B4	10	664.6	30	664.9	31	142
B5	20	704.1	14	703.8	15	117
B6	20	740.5	14	739.1	13	89
B7	20	782.8	19	779.7	19	105
B8	10	832.8	105	832.9	104	174
B8a	20	864.7	21	864.0	21	72
B9	60	945.1	19	943.2	20	114
B10	60	1373.5	19	1376	29	50
B11	20	1613.7	90	1610.4	94	100
B12	20	2202.4	174	2185.7	184	100

Source (https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/resolutions/spectral).

3.3. Atmospheric correction

Atmospheric correction is a prerequisite procedure for L1 C data for removing atmospheric effects such as absorption and scattering of reflectance value from the earth observation information. Further, atmospheric correction is more crucial in aquatic applications, particularly in the estimation of marine Chl-a and TSM. To achieve this, Neural Networks based C2RCC processors algorithms and Dark Spectrum Fitting based ACOLITE algorithms were applied.

3.3.1. ACOLITE

ACOLITE is a robust generic processor atmospheric correction algorithm by RBINS, designed and developed for coastal water. ACOLITE working principle is based on two approaches, the Exponential Extrapolation and Dark Spectrum Fitting (DSF). The present research makes use of the DSF based algorithm for generating Chl-a and TSM. The Dark Spectrum Fitting (DSF) is based on the principle that the radiance leaving the water in the darkest pixel is closer to zero. This identifies the specific areas in the images where the surface reflectance is minimal. The DSF workflow is mainly on two assumption, to a certain extent the atmosphere is homogeneous so as the path reflectance (ρ_{path}) of the satellite image and second assumption is that either one of the bands contain surface reflectance closer to zero ($\rho_s \approx 0$), where (ρ_{path}) can be calculated (Vanhellemont 2019).

3.3.1.1. C2RCC processor. Case-2 Regional Coast Colour (C2RCC), a deep learning atmospheric correction approach mainly designed for case II water. The spectrum inversion for the atmospheric correction is carried out through trained neural networks (Schiller and Doerffer 1999). The driving force of C2RCC is its comprehensive repository of modelled water-leaving reflectance and its associated radiance information. Optically complex coastal water conditions are characterized through their inherent optical properties (iop) and coastal atmosphere, is used for the parametrization of radiative transfer modes for the water body and atmosphere. A comprehensive reflectance database is generated from the covariances between water constitutes. Further, this reflectance applied in the radiative transfer calculation of atmospheric lower boundary condition (Brockmann et al., 2016). The methodological concept of the present research shown in the Fig. 2.

4. Results

4.1. Investigating the algorithm's performance with In-Situ data

One of the main objectives of this research is to identify an algorithm that aligns with the unique marine climatological conditions and the

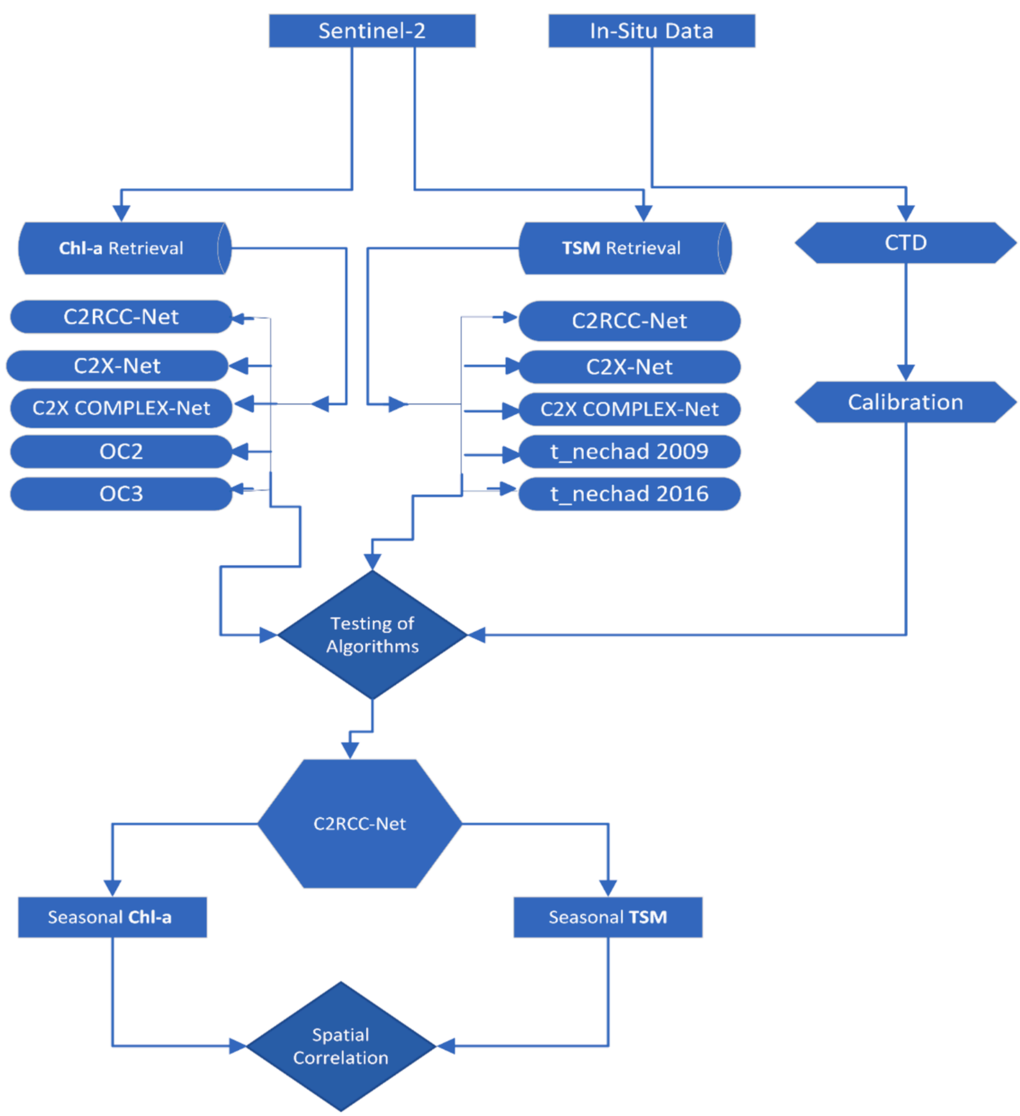

Fig. 2. Methodological Framework: Data Acquisition to Result.

influences of the Tiber River in the study area. In general, algorithm performance typically demonstrates higher efficiency near the river mouth and exhibits variability as one moves away from it. This variability can be attributed primarily to diverse marine climatological conditions and varying plume intensity. The current study evaluated ten algorithms, five for Chl-a and five for TSM. Sentinel-2 derived Chl-a and TSM information were correlated with the in-situ data to validate the efficiency and reliability of the algorithm. Apart from refining the algorithm, the present research focused on finding the best-fit algorithm by validating with in-situ data.

In the process of investigating the best-fit algorithm, the present research validated the in-situ data against Sentinel-2 derived Chl-a and TSM information using correlation, regression, Root Mean Square Error (RMSE), and BIAS tests. Optimal algorithm selection for the current research is based on two characteristics: algorithms with higher correlation coefficients and coefficient of determination along with consistent performance in the entire study area, irrespective of seasonal and climate conditions. Statistically significant relationships were observed between the algorithm outputs and the in-situ data, as indicated by multiple statistical tests including correlation, regression, and error metrics. The scatter plot between in-situ and Sentinel-2 derived Chl-a and TSM is shown in Appendix 1. Sentinel-2 based Algorithm's performance against in-situ for the Chl-a is shown in Fig. 3 and TSM is shown in Fig. 4.

4.1.1. C2RCC-Net vs. in-situ

Multiple statistical analyses were performed to evaluate the potential of the C2RCC-Net algorithm. Statistically significant relationships were observed between the in-situ data and the Chl-a and TSM estimates derived from C2RCC-Net. The C2RCC-Net algorithm demonstrated strong performance in Chl-a estimation, with a relatively high R2 value of 0.903, indicating that 90.4 % of the variance in the in-situ data is explained by the model. A high correlation coefficient of 0.950 indicates a very linear relationship between the model's predictions and the observed data. A relatively low RMSE of 0.798 indicates that the predictions are close to the actual values, while a BIAS of 0.284 indicates a minor average deviation.

Similarly, for TSM, the C2RCC-Net algorithm shows robust performance, with an R^2 value of 0.903 and a correlation coefficient of 0.950, underlining the strong linear relationship between the modelled data and the in-situ data. However, the RMSE of 1.016 for TSM is slightly higher compared to other algorithms, and the BIAS value is 0.810. Several factors contribute to the higher RMSE value, such as the normalization of Sentinel-2 resolution to 60 m, which may not adequately capture the fine-scale TSM variation observed in the in-situ data. Another factor could be the complexity of the Tyrrhenian coast, pointing to some limitations of the C2RCC-Net.

Despite the relatively high RMSE, the C2RCC-Net algorithm still demonstrates substantial explanatory power and a strong correlation coefficient, indicating it is a useful tool for estimating TSM. However, recognizing the inherent limitations and potential sources of error is crucial for refining the algorithm and improving accuracy in future studies.

4.1.2. C2X NetVs. in-situ

To evaluate the performance of the C2X Net algorithm, statistical analysis was conducted comparing in-situ measurements and algorithm-derived information. For Chl-a, a moderate R^2 value of 0.680 indicates that approximately 68 % of the variance in Chl-a is explained by the model. However, a strong correlation coefficient (0.8248) is observed, though not as high as C2RCC-Net. The RMSE of 1.9257 and BIAS of 1.2519 indicate larger errors and a tendency to overestimate.

C2X-Net shows moderate performance with an R^2 of 0.73199, explaining 73.2 % of the variance in TSM. The correlation coefficient (0.8555) is strong. The RMSE (0.9100) and low BIAS (0.04081) indicate reasonable accuracy. C2X-Net has slightly better performance for TSM estimation compared to Chl-a. Though the RMSE is less than that of C2RCC-Net, the lower correlation coefficients and coefficients of determination make it less robust.

4.1.3. C2X complex net vs. in-situ

Similarly, distinct results were obtained while analyzing the C2X Complex Net algorithm-derived and in-situ information. C2X Complex Net performs well with an R^2 of 0.79833, explaining 79.8 % of the variance. The correlation coefficient (0.8934) indicates a strong relationship. The RMSE (0.51326) and slight negative BIAS (0.4505) suggest good accuracy and a minor underestimation, indicating consistent performance.

C2X Complex Net has a better performance for TSM with an R^2 of 0.87816, explaining 87.8 % of the variance. The correlation coefficient (0.9371) indicates a strong relationship between model predictions and observed data. The RMSE (1.2602) and negative BIAS (0.4571) suggest good accuracy with slight underestimation.

4.1.4. OC2 and OC3 vs. in-situ

The OC2 and OC3 are multi-band empirical algorithms developed to estimate Chl-a concentrations using remote sensing reflectance of blue/green ratios. OC2 has a moderate R^2 of 0.7993, explaining 79.9 % of the

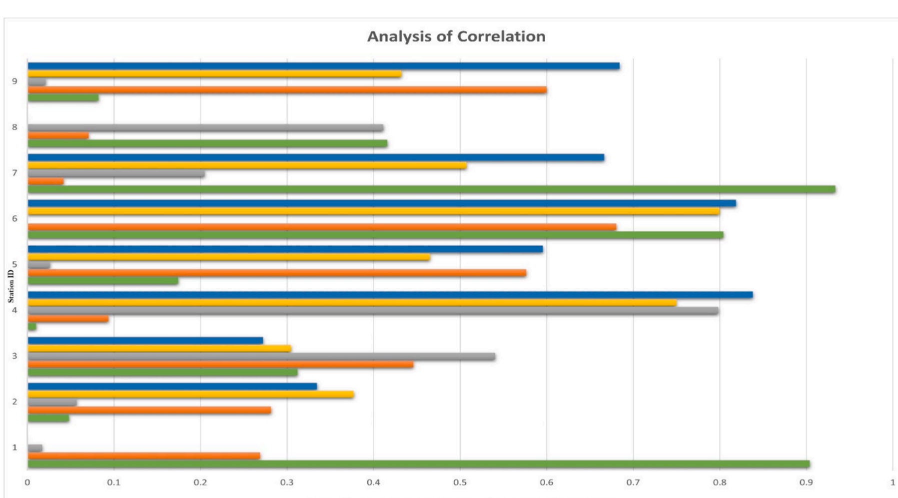

Fig. 3. Analysis of Correlation, Chl-a-: In-Situ Vs. Algorithmic Result.

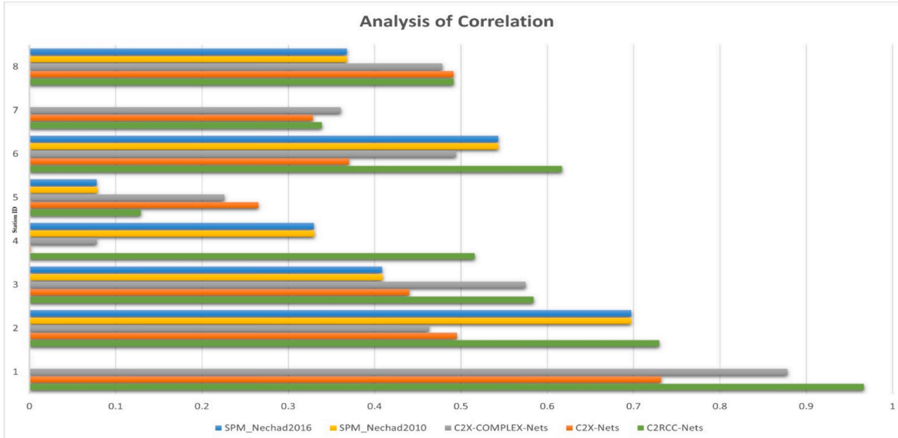

Fig. 4. Analysis of Correlation, TSM: In-Situ Vs. Algorithmic Result.

variance. The correlation coefficient (0.8940) indicates a strong relationship. The RMSE (0.5892) and BIAS (0.5307) are moderate, indicating reasonable accuracy with some overestimation.

OC3 demonstrates strong performance with an R^2 of 0.8381, explaining 83.8 % of the variance. The correlation coefficient (0.915475) is very high, indicating a strong linear relationship. The very low RMSE (0.2672) compared to other algorithms and BIAS (0.0508) suggest accurate predictions with minimal deviation, indicating better consistency.

4.1.5. t_nechad and t_nechad2016 vs. In-situ

The t_nechad and t_nechad2016 algorithms use empirical relationships with specific coefficients for Landsat-8 and Sentinel-2. The default wavelength for the red band is used, and 833 nm for Sentinel-2 in t_nechad2016. The t_nechad algorithm shows lower performance with an R^2 of 0.6969, explaining only 69.7 % of the variance in TSM. The high RMSE (1.3610) and BIAS (1.1999) indicate significant errors and overestimation. Similarly, t_nechad2016, with an R^2 of 0.69745, also shows high RMSE (1.2500) and BIAS (1.0951), indicating significant errors and overestimation. These results highlight that, under the present study area conditions, both algorithms exhibit similar performance levels in delineating TSM.

Overall, the study demonstrates that the C2RCC-Net algorithm shows robust performance for both Chl-a and TSM estimation. The inherent spatial and temporal variability of coastal environments like the Tyrrhenian Sea presents challenges for achieving perfect accuracy. Future research could focus on improving algorithmic adjustments to better capture fine-scale variability and integrating more frequent temporal data to enhance estimation accuracy.

4.2. Seasonal dynamics of Chl-a and TSM

Investigating the seasonal distribution and estimation of Chl-a and TSM helps to understand the dynamic interplay between the Tiber River influence, anthropogenic impacts, and marine biophysical-climatological impacts. Moreover, the estimation and distribution of Chl- a and TSM are prerequisite for a comprehensive understanding of coastal ocean and sea process and management. Continuous monitoring and measuring of Chl-a and TSM provide ambient information about the potential impacts of environment and climate change. Based on the

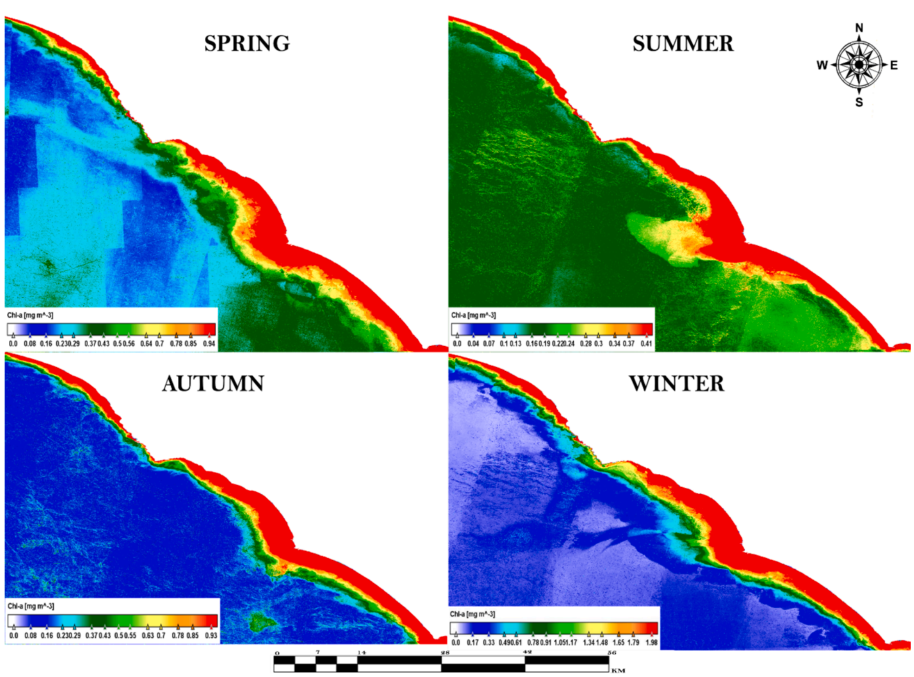

Fig. 5. Seasonal Distribution of Chl-a.

analysis of correlations between the in-situ and selective algorithm analysis, the present research makes use of the C2RCC-Net algorithm for estimating the seasonal dynamics of Chl-a and TSM. The estimated seasonal dynamics of Chl-a and TSM is shown in the Figs. 5 and 6.

4.2.1. Spring

Chlorophyll-a concentration in the study area exhibits significant seasonal variability, the estimated Spring Chl-a concentration ranges between 0 and 0.94 [mg m^{-3}]. This increasing Chl-a indicates a higher level of phytoplankton abundance. Favourable climatic and environmental conditions, including increased nutrient availability from Tiber River, and the spring bloom. Higher Chl-a concentrations are registered over the Tiber mouth region, and gradually diminish with lower intensity towards Anzio region. Meanwhile, the TSM for the season ranges from 0 to 1.49 [mg/m^3], shows a relatively less concentration but similar dynamic characteristics of Chl-a concentration. The distribution of TSM and Chl-a is mainly dependent on the prevailing tidal conditions, sediment size and rate of Tiber River sediment load. During spring, the Tyrrhenian region experiences moderate rainfall, which contributes to the higher discharge rates of the Tiber River. Sea surface temperatures begin to rise, supporting phytoplankton growth.

4.2.2. Summer

The average summer estimation of Chl-a for the research area ranges between 0.0 and 0.4 [mg m^{-3}] and for TSM is 0.0 to 0.8 [mg/m^3], respectively. Several factors contribute to this below moderate condition. During the summer the Tyrrhenian Sea temperature increase, and it ranges from 25 °C to 30 °C, which is above the optimal temperature conditions of the phytoplankton growth. Increasing summer temperatures accelerate the evaporation rate and which leads to increasing salinity, and which limits the dissolved nutrients level. Nutrient availability is another limiting factor, during the summer season due to less precipitation the Tiber River inputs are limited and large uptake of nutrients by the phytoplankton resulted from the Spring bloom are also a factor. Lower summer sediment conditions are mainly influenced by the less summer precipitation which ultimately results in the Tiber River nutrient load.

4.2.3. Autumn

The seasonal average of the Chl-a and TSM for the Autumn ranges from 0 to 0.9[mg m^{-3}] and 0 to 1.63 [mg/m^3] respectively. During this period Tyrrhenian Sea temperature is reached between 15 to 20 °C which is highly optimum for the phytoplankton growth. The decline in sea temperature increases water column mixing, which accelerates the growth rate of Chl-a and increase the level of TSM. The autumn precipitation amplifies the sediment release from the Tiber River, influencing the nutrient level and leading to an increase in the Chl-a and TSM level. The recirculation of sunken organic matter during the summer season has a vital role on Chl-a rate by accelerating the nutrient level. The tidal currents are stronger during the season, which leads to wide distribution of TSM from the river mouth to all over the region and elevating its surface level concentrations. Autumn brings increased precipitation to the Tyrrhenian region, raising the discharge rates of the Tiber River and contributing to coastal sediment loads. Cooler sea surface temperatures and reduced sunlight influence the TSM and Chl-a concentration.

4.2.4. Winter

Winter season recorded a highest concentration level of Chl-a and TSM among all season, measuring 0–1.977 [mg m^{-3}] and 0–3.01535 [mg/m^3] respectively. The result suggests that marine climatological conditions during the winter season are highly favourable for the growth of Chl-a and TSM in the study area. The upwelling events are pronounced during the winter season in the Tyrrhenian region, which enhances the nutrient level. This results in increasing phytoplankton, despite the lower sea temperature. Tiber River discharge is higher during the season due to shifting of seasonal changes heightened the sediment discharge, which is reflected in the observed TSM level. Further increased water column stability and less grazing pressure from the zooplankton during winter are also another supporting factor for the higher Chl-a concentration. Winter is characterized by frequent storms and high precipitation, leading to the highest discharge rates from the Tiber River. These conditions result in significant sediment input from the river and increased resuspension of sediments due to strong winds and turbulent seas.

The seasonal variations in Chl-a and TSM concentrations in the Tyrrhenian region reflect the complex interplay between biological and

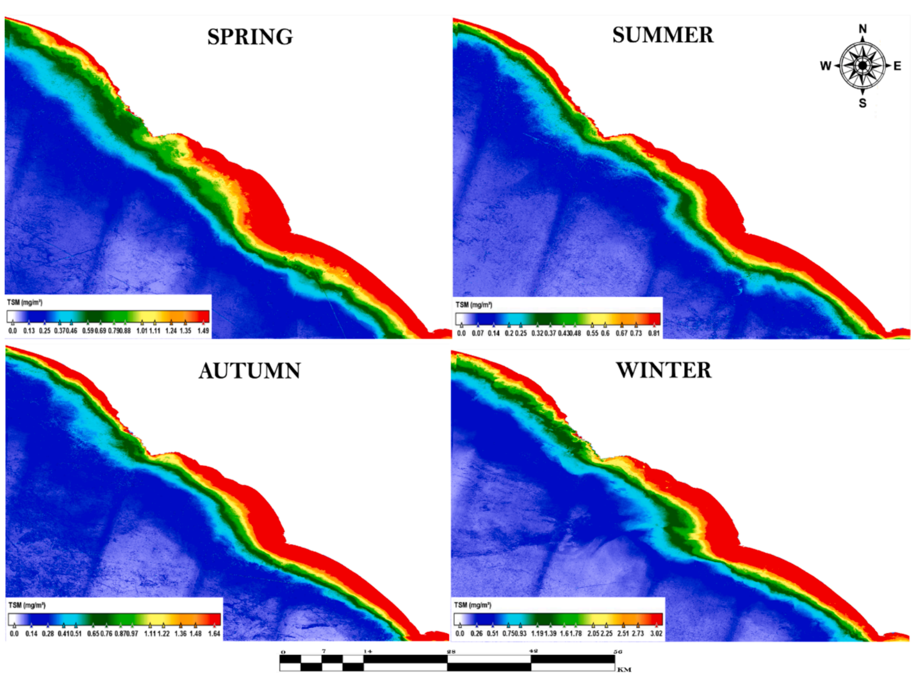

Fig. 6. Seasonal Distribution of TSM.

physical processes, influenced by weather conditions, river discharge, and sea surface temperatures. In spring, nutrient inputs and favourable conditions enhance phytoplankton growth and sediment resuspension, leading to higher Chl-a and TSM levels. In summer and autumn, the decline in sunlight and temperature reduces productivity and TSM levels. Winter marked significant increase nutrient availability and phytoplankton growth, resulting in elevated Chl-a and TSM concentrations. Understanding these patterns is crucial for effective marine resource management and predicting the impacts of environmental changes on the ecosystem's health.

4.3. Spatial correlation

Spatial correlation analysis serves as a powerful method for the deep understanding of the complex interrelationship between the Chl-a, TSM, and the influence of Tiber River along the Tyrrhenian coast. Considering the declining trend of Chl-a in the Mediterranean Sea and the ambivalent relationship between the Chl-a and TSM, it is highly essential to assess the role of Tiber River in the Tyrrhenian marine productivity. Pixel to pixel correlation method adopted to understand the spatial correlation between TSM and the Chl-a concentration. For a better understanding of its long-term spatial relationship, Sentinel-2 seasonal information from December 2015 to September 2023 were processed. Initially, scatter plots were generated to observe the general spatial correlation trend of the Chl-a and TSM. Positive spatial correlation observed in all the seasons as indicated in the Fig. 7. Subsequently, Sentinel-2 derived seasonal Chl-a and TSM data sets were subjected to the pixel-to-pixel correlation. A correlation coefficient +1 (green colour) indicates positive relationship, while −1 (orange colour) signifies negative relationship (Fig. 8).

In summary, the spatial correlation analysis reveals a positive relation between the Chl-a and the TSM in all four seasons. This positive correlation indicates that the Chl-a concentration increases along with increase in TSM. Essentially, the Tiber River have a positive impact on the Tyrrhenian marine productive system. As illustrated on the Fig. 8. A higher positive correlation is observed during the winter season (range = -0.89 to 0.99, Mean = 0.445) followed by Autumn (range = −0.88 to 0.99, Mean = 0.413), Spring = −0.89 to 0.99, Mean 0.367) and Summer (range = −0.85 to 0.99, Mean = 0.362). Several factors contribute to this positive correlation, including type and productivity of phytoplankton, level of nutrient input and coastal hydrodynamic conditions.

However, there are exceptions to this positive trend in the study area. Negative correlation has been observed in offshore regions of the study area, indicating instance where Chl-a concentration is decreases with increase in TSM or vice versa. Summer season has more areas exhibiting negative correlation compared to other seasons.

5. Discussion

Remote sensing of marine Chl-a and TSM are challenging and establishing their relationship is complex. The present research mainly focused on understanding the pivotal role of the Tiber River in Tyrrhenian primary productivity. Recent studies have highlighted a declining trend in Chl-a concentrations across the Mediterranean seas. Heavy terrestrial loads are a key limiting factor for Chl-a, and given the sediment load of the Tiber River, it is essential to assess its impact on primary productivity in the Tyrrhenian Sea. Our research demonstrates a positive correlation between Chl-a and TSM, indicating that higher levels of TSM are associated with increased concentrations of Chl-a. In contrast to the present research observation, (Yamaguchi et al., 2013) observed a negative correlation between Chl-a and TSM in the Yellow and East China Seas. The study highlighted that in areas with high concentrations of resuspended sediment, Chl-a levels were lower, indicating a negative impact of TSM on Chl-a concentrations.

5.1. Algorithmic performance

Identifying the most suitable algorithm for estimating the seasonal dynamics of Chl-a and the TSM is challenging due to the marine climatological conditions and the influences of the Tiber River. Marine climatological conditions and varying plume intensities lead to both over and under evaluation of the variables. Additionally, the availability and quality of in-situ data pose another constraint. The analysis of algorithms reveals significant variation in their performance in estimating Chl-a and TSM. Given its higher correlation coefficient of 0.950 (Chl-a) and R^2 value of 0.903 (Chl-a) with a consistent performance across the

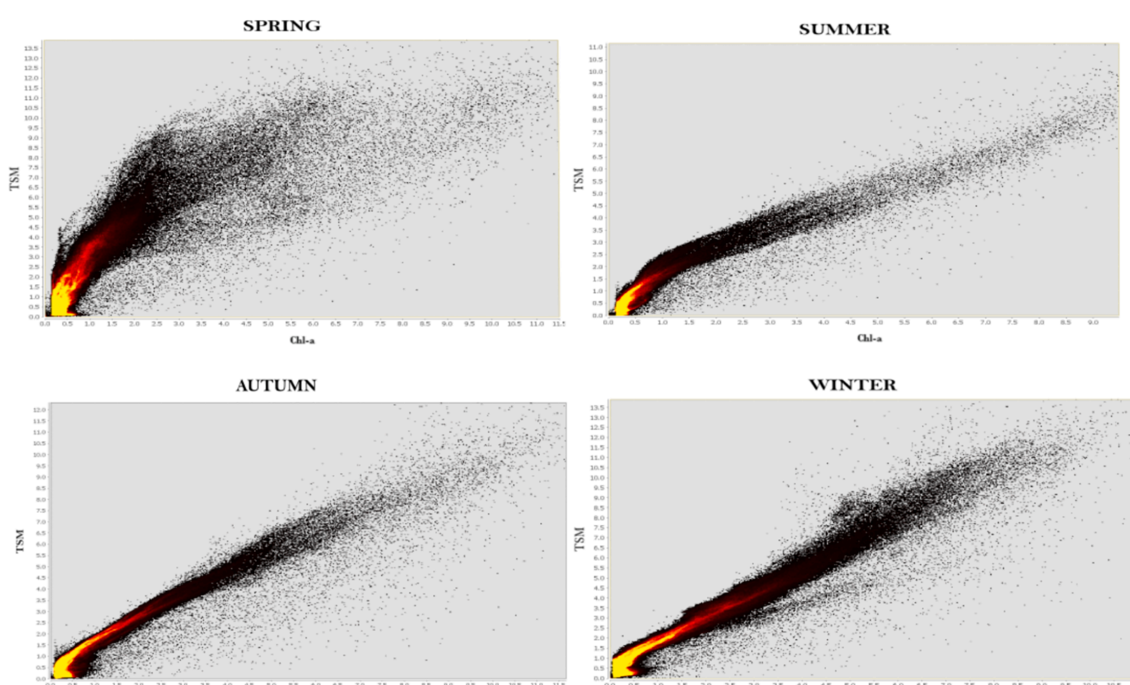

Fig. 7. Scatterplot of Seasonal Chl-a Vs. TSM.

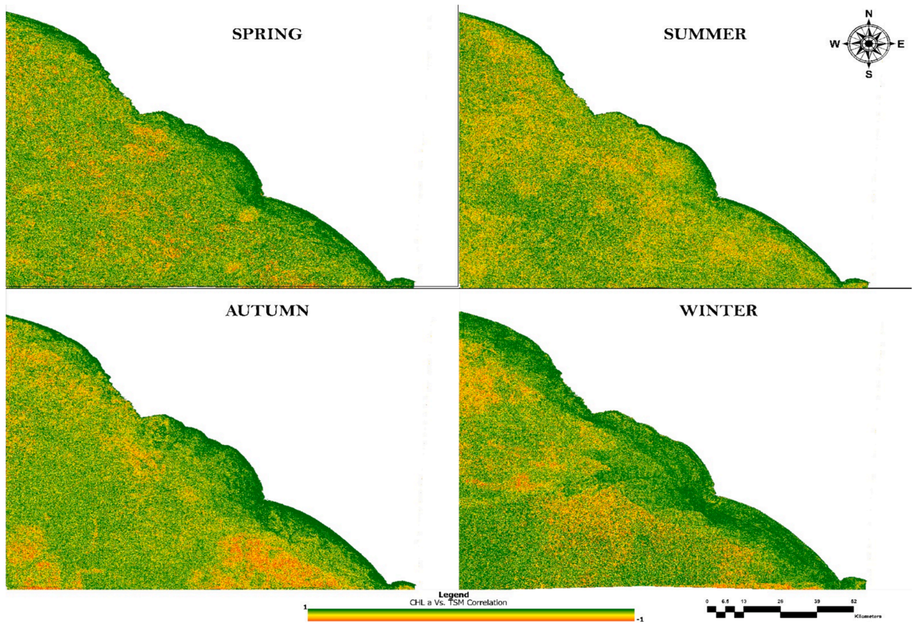

Fig. 8. Seasonal Spatial Correlation of Chl-a Vs. TSM.

study area, C2RCC-Net is selected as the most suitable algorithm for the estimating Chl-a. The OC3, algorithm demonstrates consistent performance in the study, however the algorithm result exhibit zero correlation with multiple in-situ station data and failed to achieve a higher correlation coefficient in compared to C2RCC-Net.

In TSM estimation, the C2RCC-Net algorithm consistently demonstrated a superior accuracy in with a statistically significant positive correlation of 0.966 and R^2 value of 0.983 with in-situ data. However, in the TSM estimation, C2X-Complex-Net demonstrated an appreciable performance in comparable to C2RCC-Net, with a correlation coefficient of 0.9371. Similarly, this good trend was observed in OC3 (r 0.915) for Chl-a estimation. Analysing correlation finding provides valuable insights into the algorithm selection and highlight the need for validating the algorithm's performance with in-situ data, as it is highly dependent on the study area conditions. Overall, the results underscore the promising performance of C2RCC-Net for the accurate measurement of Chl-a and TSM. Further analysis and studies are required to understand the controlling factors behind the observed differences in the algorithm performance.

5.2. Seasonal distribution analysis

The seasonal distribution analysis of Chl-a and TSM will provide a valuable insight into the dynamic interplay between the Tiber River influence and the marine biophysical-climatological impacts on the Tyrrhenian region. The increasing Chl-a concentration during the spring season linked to phytoplankton bloom due to favourable climatic conditions and nutrient availability from the Tiber River. A similar trend is observed in the TSM, influenced by prevailing tidal conditions and sediment rate. The correlation was assessed using a colour scale where green indicates positive correlations, red indicates negative correlations, and yellow/orange indicates weaker or more variable correlations. The summer season exhibited a lower concentration of both Chl-a (0–0.4 mg m^{-3}) and suspended sediment concentration (0–0.8 mg/m^3). This declining trend is mainly because of increased sea temperatures, changes in salinity and limited nutrients supply. These conditions align with the known Mediterranean summer conditions of the Chl-a and TSM dynamics.

The autumn season demonstrated higher levels of Chl-a (0–0.9 mg m^{-3}) and TSM (0–1.63 mg/m^3) compared to Summer. Several factors contributed to these sudden changes in Chl-a and TSM, including mixing of water column and sediment discharge due to active autumn precipitation. The winter season recorded the highest levels of Chl-a (0–1.977mg m^{-3}) and TSM (0–3.01535 mg/m^3) compared to all other seasons. Factors such as upwelling events, stable water column conditions and increased river flow influenced by the shifting of seasonal changes due to changes in climate variations, may also contribute to these favourable conditions.

5.3. Spatial correlation analysis

The spatial correlation analysis provides a deeper understanding of the Tiber River's impacts on the complex spatial relationship between Chl-a and the TSM along Tyrrhenian coast. The scatterplot revealed a positive correlation pattern across all the season. During the spring there is a dense cluster of data points at lower values of Chl-a (0.5–3.5) and TSM (0–5), showing the Chl-a increase with TSM. This could associate with increased variability in the environmental conditions. During the summer the data point seems more consistent with steeper slope, suggesting positive correlation between Chl-a and TSM, this might be due to the increased sunlight and warmer temperature. Autumn pattern is like spring, but with a slightly wider spread in data point, clear indication of increasing Chl-a with TSM. The winter data point forms a dense cluster at lower values, with an extended tail like spring and autumn. The distribution is again concentrated at lower end, with a positive correlation. In summary, the scatterplots reveal a consistent positive relationship between TSM and Chl-a across all seasons, with most data concentrated at lower values and increasing spread and variability at higher values.

In spring, predominantly positive spatial correlation observed between Chl-a and TSM, as indicated by the extensive regions on the map. This period is typically characterised by higher levels of nutrient availability from the Tiber River, increased phytoplankton activity and spring blooms. During the summer, the positive correlation remains but with slight decrease in strength as evidence by more yellow region. This variation may be due to the increased temperature, less nutrient supply from the Tiber River due to less precipitation. Additionally, the higher temperature may increase the decomposition rate of organic matter. In autumn, positive correlation observed along the Tyrrhenian coastal ocean and seas, with noticeable increase in yellow areas indicating regions with weak or no correlation. There are several contributing factors associated with this condition which includes, declining of temperature, stratification break down, leading to resuspension of sediments. The changes in correlation pattern may also relate to the transition period in the marine aquatic ecosystem, where biological and physical process are adjusting to the forth coming winter conditions. The winter season shows a return to stronger positive correlation with widespread green areas, indicating a strong positive correlation between Chl-a and TSM. This could be due to the higher nutrient discharge from the Tiber River, mixing of water column, the strong positive correlation suggests that despite the lower temperature, the interaction between Chl-a and TSM is robust, potentially driven by increased nutrient availability from resuspended sediments. Overall seasonal variations in the correlation between Chl-a and TSM in the Tyrrhenian region highlight complex interactions between biological activity, nutrient availability and physical process within the marine ecosystem.

The observed positive correlation near the coast, in all four seasons indicates that Chl-a increases with an increase in TSM level, which is evident on the positive impact of Tiber River's discharge on the Tyrrhenian marine productivity. The variations in seasonal correlation strength are attributed to phytoplankton productivity, nutrient input levels and coastal hydrodynamics. Notably, exceptions in the form of negative correlation were identified in all seasons with a higher occurrence observed in summer and spring, however along the coastline positive correlation remained evident. This is possibly due to anthropogenic influences or due to other factors which require more scientific attention. The overall seasonal positive correlation also emphasizes that the Tiber River load positively impacts Chl-a levels along the Tyrrhenian coastline, in contrast to the negative trend observed in the Mediterranean region. Overall, the TSM shows no negative impact on this relationship, except in some regions. which require further studies.

6. Conclusion

In conclusion, the present research provides a comprehensive understanding of the role of the Tiber River in the Tyrrhenian Sea's primary productivity, particularly through the relationship between Chl-a and TSM. The key finding includes the consistent positive correlation between Chl-a and TSM across all seasons, indicating that higher sediment loads from the Tiber River are associated with increased Chl-a concentrations, this contrasts with trends observed where sediment loads often limit Chl-a levels. Among the algorithm assessed, C2RCC-Net consistently demonstrates the highest accuracy and strongest predictive performance across both Chl-a and TSM data sets, as evident by its high correlation coefficient and R^2. The research underscores the importance of algorithm selection and validation based on in-situ data, as its performance is highly associated with local environmental conditions.

Sentinel-2 plays a crucial role in this context by providing high-resolution information that is essential for monitoring these dynamics and enhancing the accuracy of algorithms. In our study area, the current research identified C2RCC-Net as a promising algorithm for the estimation of Chl-a and TSM from Sentinel-2 data. The present research contributes valuable insights for the Sentinel-2 based algorithm selection for marine environmental monitoring, and management practices. The correlation between Chl-a and TSM in the Tyrrhenian coastal region exhibits clear seasonal variability and a positive relationship. Further, the research findings have important implications for future research and marine management practices. The study suggests the need for further refinement and validation of remote sensing algorithms, particularly to address seasonal and regional variations in performance. Sentinel-2′s capabilities play a vital role in this process by offering detailed data that can enhance our understanding of the factors driving these variations, including the observed negative correlations in some regions. Moreover, the positive impact of the Tiber River's sediment load on Tyrrhenian productivity, as revealed through Sentinel-2 data, provides valuable insights for managing coastal ecosystems. This involves balancing nutrient input and sediment flow to optimize marine health and productivity, making Sentinel-2 a key tool for both research and practical applications in marine management.

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CRediT authorship contribution statement

Dani Varghese: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Viviana Piermattei:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Alice Madonia:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Marco Marcelli:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jag.2024.104161.

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